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Prospects for CP violation in LHCb

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1 Introduction

This document describes the current expectations for two important CP violation measurements of the LHCb experiment. For a theoretical overview of the CP violation phenomenology, one can refer to [1] and [2]. The description of the LHCb experiment is given in detail in the reference [3]. The first part of this document presents the status of the sensitivity studies of the $\mathrm{B_s^0}$ mixing phase $\phi_\mathrm{s}^{\mathrm{J}/\psi\phi}$ in the decays $\mathrm{B_s^0} \to \mathrm{J}/\psi\phi$, together with the phase $\phi_\mathrm{s}^{\phi\phi}$ from the decays $\mathrm{B_s^0} \to \phi\phi$. We also give the expected results on the calibration measurement of $\sin(2\beta)$ with $\mathrm{B_d^0} \to \mathrm{J}/\psi\mathrm{K_S^0}$ decays. The second part gives the sensitivity to the CKM angle γ. This part is subdivided in two sections, the first one presents the extraction of γ in the "tree" level dominated decays $\mathrm{B} \to \mathrm{DK}$ and the second one presents the sensitivity in the "penguin" level decays $\mathrm{B} \to \mathrm{hh}$.

2 Measurement of the $\mathrm{B_s^0}$ mixing phase

2.1 Analysis of $\mathrm{B_s^0} \to \mathrm{J}/\psi\phi$ decays

The interference between $\mathrm{B_s^0} \to \mathrm{J}/\psi\phi$ decays with and without $\mathrm{B_s^0} - \overline{\mathrm{B}}_\mathrm{s}^0$ oscillation gives rise to the CP violating parameter $\phi_\mathrm{s}^{\mathrm{J}/\psi\phi}$. This is represented in Figure 1. In the Standard Model, when penguin contributions to the decay amplitude are neglected, this phase is predicted to be:

$$\phi_\mathrm{s}^{\mathrm{J}/\psi\phi} = -2\beta_\mathrm{s} = 0.0360^{+0.0020}_{-0.0016}\,\mathrm{rad} \tag{1}$$

where $\beta_\mathrm{s} = \arg(V_{ts}V_{tb}^*/V_{cs}V_{cb}^*)$. This phase could be modified by New Physics contribution to the $\mathrm{B_s^0} - \overline{\mathrm{B}}_\mathrm{s}^0$ mixing.

The TeVatron experiments [4, 5] yield the following constraint:

$$\phi_\mathrm{s}^{\mathrm{J}/\psi\phi} \in [-2.6, -1.94] \bigcup [-1.18, -0.54]\,\mathrm{rad}\ \mathit{at}\ 68\%CL\,, \tag{2}$$

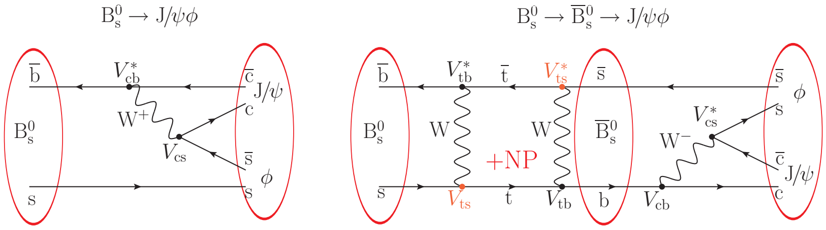

Figure 1: $B_s^0 \to J/\psi\phi$ decays with and without $B_s^0 - \overline{B}_s^0$ oscillation. The interference between both process gives rise to the $\phi_s^{J/\psi\phi}$ phase.

compatible with the Standard Model prediction value at the 2σ level.

The measurement itself is performed studying the time dependent decay rates of the $B_s^0 \to J/\psi\phi$ decays. This measurement is complicated by the following:

- the decay is $P \to VV$, so it requires an angular analysis of the final state particules to disentangle statistically the different CP-odd and CP-even components,
- the decay width difference between the two mass eigenstates of the B_s^0, $\Delta\Gamma_s$, is expected to be very large compared to the one of the B_d^0 mesons,
- the oscillation frequency Δm_s of the B_s^0 mesons is very large compared to the oscillation frequency of the B_d^0 mesons [6, 7], so it requires a good proper time resolution to see the oscillations.

The LHCb experiment expects to gather 117k events for one nominal year of running, *i.e.* $2\,\mathrm{fb}^{-1}$ of integrated luminosity, with a $B/S \approx 2.1$. The proper time resolution is expected to be $\approx 40\,\mathrm{fs}$, and the B_s^0 invariant mass resolution is expected to be $16\,\mathrm{MeV}/c^2$. The measured angles for the angular analysis show distortions of less than 10%, and the effective tagging power (εD^2) is $\approx 6.2\%$ [8].

The $\phi_s^{J/\psi\phi}$ sensitivity has been estimated to be:

$$\begin{aligned} \mathcal{L} = 0.5\,\mathrm{fb}^{-1} &\;:\; \sigma(\phi_s^{J/\psi\phi}) \sim 0.060, \\ \mathcal{L} = 2\,\mathrm{fb}^{-1} &\;:\; \sigma(\phi_s^{J/\psi\phi}) \sim 0.030 \end{aligned}$$

in the nominal running conditions, with large errors coming from the $b\overline{b}$ production cross section and the visible branching ratio.

Systematic effects due to proper time and angular resolution, angular acceptance and flavor tagging have been studied and found to be smaller than the statistical uncertainty expected for $2\,\mathrm{fb}^{-1}$. The Figure 2 shows the evolution of the sensitivity according to two LHC running scenarii. The blue lines show the uncertainties related to the $b\overline{b}$ cross section and the visible branching ratio of $B_s^0 \to J/\psi(\mu\mu)\phi(KK)$. The black horizontal line is the combined CDF/D0 uncertainty in 2008 scaled to an

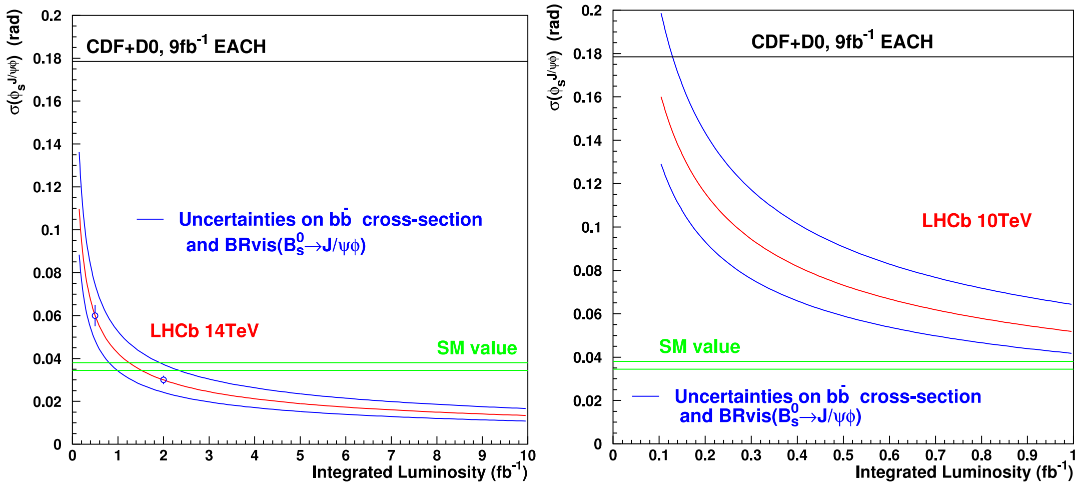

Figure 2: Expected LHCb sensitivity on $\phi_s^{J/\psi\phi} = -2\beta_s$ as a function of the integrated luminosity. The plot on the left indicates the evolution for a nominal LHC running condition, $E_{CM} = 14\,\mathrm{TeV}$, while the plot on the right shows the same evolution, but with a LHC energy of $E_{CM} = 10\,\mathrm{TeV}$. We also indicate the expected sensitivity for the TeVatron and the Standard Model prediction.

integrated luminosity of $2 \times 9\,\mathrm{fb}^{-1}$, as expected for the two TeVatron experiments by 2010. It should be noted that if the TeVatron measurement is confirmed, LHCb should discover New Physics at the 5σ level with only $0.2\,\mathrm{fb}^{-1}$.

2.2 Analysis of $B_s^0 \to \phi\phi$ decays

Contrary to the $B_s^0 \to J/\psi\phi$ decays, the $B_s^0 \to \phi\phi$ decays occur by a penguin process, as illustrated in Figure 3. Due to the presence of the CKM matrix element V_{ts} in the decay, the total weak phase cancels. Therefore, neglecting the contribution from the penguin process involving u and c quarks, the mixing phase is predicted to be $\phi_s^{\phi\phi} = 0$

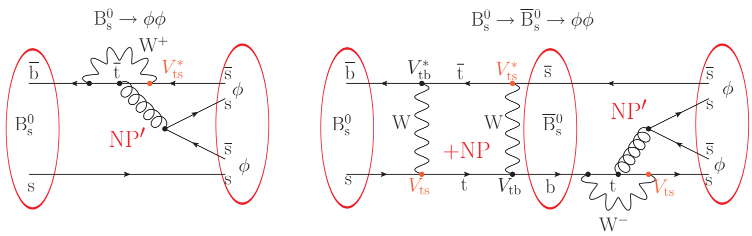

Figure 3: Illustration of the $B_s^0 \to \phi\phi$ decays, with and without $B_s^0 - \overline{B}_s^0$ oscillation.

in the Standard Model. Only a contribution from New Physics can make this phase deviate from 0.

It presents the same difficulties for the analysis than for the $B_s^0 \to J/\psi\phi$ decays study, with a lower expected yield due to the decay process occuring only through a loop diagram.

In the spectator quark model, this decay is very similar to the decays $B_d^0 \to \phi K_S^0$ and $B_d^0 \to \eta' K_S^0$, so the penguin contributions in the decay amplitudes can be factorized.

The LHCb expected selection yield is 6.2 k events for $2\,\mathrm{fb}^{-1}$ with a $B/S < 0.8$. The sensitivity on $\phi_s^{\phi\phi}$ with these statistics is $\sigma(\phi_s^{\phi\phi}) \approx 0.08$.

Used in association with the measurement of $\phi_s^{J/\psi\phi}$, this measurement can be used to constrain New Physics in the mixing and in the penguin decay.

2.3 Calibration with the measurement of $\sin(2\beta)$ in $B_d^0 \to J/\psi K_S^0$ decays

The measurement of $\sin(2\beta)$ is used in LHCb as a calibration channel [9]. It is used because it shares the same trigger line than $B_s^0 \to J/\psi\phi$ decays, and the selection procedure uses the same criteria for the J/ψ selection. The opposite side tagging algorithm is expected to behave identically, so that the mistag fraction are compatible. Moreover, both decays use the same tools, apart from the angular measurements, as $B_d^0 \to J/\psi K_S^0$ is not a $P \to VV$ decay. Finally, both measurements require identical control channels.

With $2\,\mathrm{fb}^{-1}$ of data, the expected yield is 76 k events after trigger and selection, and the sensitivity to $\sin(2\beta)$ is expected to be $\sigma(\sin(2\beta)) \approx 0.020$. This sensitivity is comparable to the world average [**?**].

3 Measurement of the CKM angle γ

The measurement of this angle is performed in LHCb studying two classes of decay processes, tree and penguin. The tree level decays are expected to be less sensitive to New Physics than the penguin level decays. The analysis of the tree level decays is performed using the methods known as GLW [11], ADS [12], and GGSZ [13], and the time dependent analysis of $B_s^0 \to D_s K$ decays. The penguin process is studied using the analysis of $B \to hh$ decays.

3.1 γ with tree level decays

The GLW and ADS methods are counting experiments. The first one is interested in $B^+ \to D^0 K^+$ decays with $D^0 \to \pi^+\pi^-$ or $D^0 \to K^+K^-$, while the second studies flavour

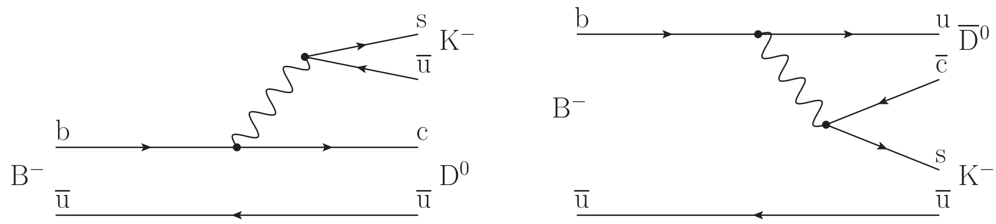

Figure 4: Feynman diagrams at leading order of the $B \to DK$ decays. Left: Cabibbo-allowed decay. Right: Cabibbo-suppressed decay. The phase difference between the two modes is $\gamma - 2\beta$.

	B^+	B^0_d
Cabibbo allowed	84 k	4 k
Cabibbo suppressed	1.6 k	360
B/S	0.6 – 3.2	0.2 – 13.5

Table 1: Expected yield and B/S for $2\,fb^{-1}$ for the Cabibbo-allowed and suppressed modes used in the extraction of the CKM angle γ.

specific D decays $D^0 \to K^+\pi^-$. The advantage of the ADS and GLW methods used together is to mix Cabibbo-allowed and Cabibbo-suppressed decays, as illustrated in Figure 4. In parallel to the charged modes, the neutral decays $B^0_d \to D^0 K^{*0}$ are also studied in LHCb, together with the multi-body decays $B^+ \to D(K^\pm\pi^\mp\pi^-\pi^+)K^+$.

The expected yields for $2\,fb^{-1}$ of data and the B/S for the charged and neutral modes are given in Table 1. The sensitivity determined on those data samples is given in Table 2.

The GGSZ method consists in the Dalitz plot analysis of $B^\pm \to D(K^0_S\pi^+\pi^-)K^\pm$ decays. The LHCb experiments expects to collect 6.1 k events for $2\,fb^{-1}$, with a $B/S < 1.1$. The extraction of γ uses two techniques giving two different sensitivities:

- Amplitude fit: $\sigma(\gamma) = 9.8^o$,

Channel	$\sigma(\gamma)(^o)$
$B^\pm \to DK^\pm$	13.8
$B^0 \to DK^{*0}$	5.2 – 12.7

Table 2: Sensitivity to the measurement of the CKM angle γ with $2\,fb^{-1}$ using the ADS and GLW methods. In the neutral decay case, the sensitivity depends on the value of the strong phase δ_{B^0}, also extracted from the data.

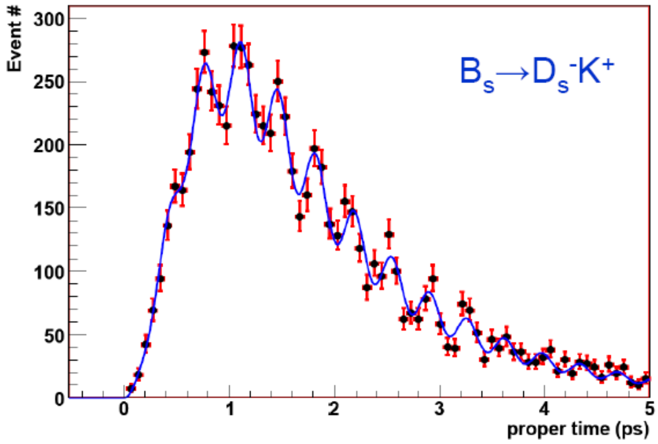

Figure 5: Reconstructed and fitted $B^0_s \to D^-_s K^+$ decay rate.

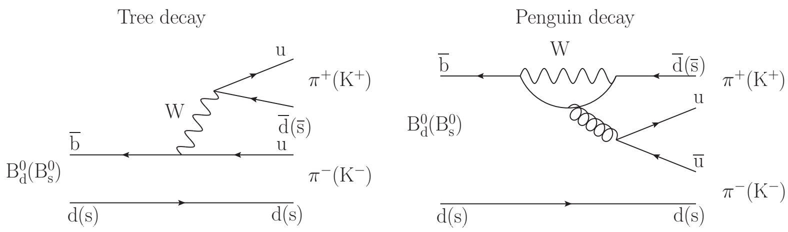

Figure 6: Feynman diagrams corresponding to the $B \to hh$ decays.

- Binned fit: $\sigma(\gamma) = 12.8^o$.

The time dependent analysis of $B^0_s \to D_s K$ decays relies on LHCb's particle identification system, with a separation $K - \pi$ in the RICH. The yield is expected to be 6.2 k with a $B/S = 0.7$ for $2\,\mathrm{fb}^{-1}$. Figure 5 shows the reconstructed and fitted decay rate for $B^0_s \to D^-_s K^+$ decays. The expected sensitivity on the CKM angle γ using only the time dependent analysis is $\sigma(\gamma) = 10.3^o$, relying on the knowledge of the B^0_s mixing angle β_s extracted from $B^0_s \to J/\psi\phi$ decays.

3.2 γ with penguin level decays

The interest of the $B \to hh$ decays is the fact that the penguin contribution to the decay diagram is not negligible compared to the tree amplitude. Therefore this decay mode is sensitive to New Physics. The corresponding Feynman diagrams are given in Figure 6.

Like the analysis of $B^0_s \to D^-_s K^+$ decays, the measurement of the CKM angle γ

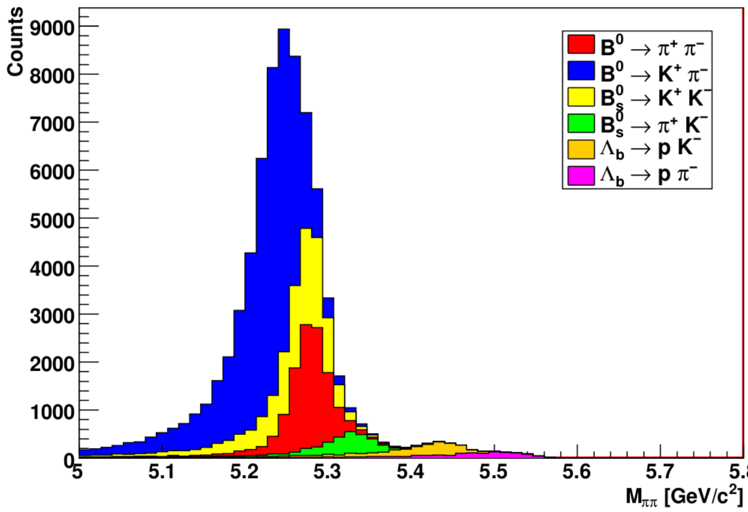

Figure 7: Reconstructed $\pi\pi$ invariant mass for different decay types. Each mode is identified using a PID hypothesis for the reconstructed pions. Without PID, there would be no separation.

with $B \to hh$ decays requires particle identification to separate the kaons from the pions. Figure 7 illustrates this separation. The extraction of the angle γ is performed through the analysis of the time dependent decay rates for the different $B \to hh$ decay modes. To be able to extract the value of γ, it is necessary to make an assumption on the U-spin symmetry between $B_d^0 \to \pi\pi$ and $B_d^0 \to KK$ decays. A study of the breaking of this symmetry to up to 20% has shown that the value of γ is not subtantially affected. The resulting sensitivity on γ is $\sigma(\gamma) = 8^o$.

4 Conclusion

The LHCb experiment is dedicated to the measurement of CP violation and the search for rare decays in the b quark sector. In this document, we presented the current results of the prospective studies towards CP violation. The expected sensitivity on the B_s^0 mixing phase $\phi_s^{J/\psi\phi}$ with $2\,\mathrm{fb}^{-1}$ of data is 0.03 rad. This sensitivity enables the LHCb experiment to probe New Physics at the level of 5σ with $0.2\,\mathrm{fb}^{-1}$ in case the current central value given by the TeVatron is confirmed. The measurements of the CKM angle γ in tree dominated decays, $B \to DK$, is extracted using three analyses, giving a combined sensitivity of $\sigma(\gamma) = 5^o$. The measurement of γ in penguin decays, $B \to hh$, gives a sensitivity of $\sigma(\gamma) = 8^o$ assuming U-spin symmetry. Those sensitivities should be compared to the current world average of $\sigma(\gamma) \approx 20^o$[10].

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